LL #51

Breaking Up Isn't Hard to Do
A View of NAPL Using Electrical Resistivity Imaging

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Characterizing a site affected by fugitive fuel products from spills, leaks from tanks and lines, or an accidental release (e.g., sudden flooding in New Orleans) is a prerequisite to any cleanup project. Knowing the lateral and vertical extent of sources and the associated environmental impact is the first step in knowing how to address these issues and to develop an appropriate project schedule and budget. On most nonaqueous-phase liquid (NAPL)-affected sites, drilling programs are the usual first step in most cleanup programs, closely followed by a best-judgment interpolation between discrete sampling data from soil borings and wells to create a site conceptual model.

This industry standard methodology has most often led to the creation of inaccurate site conceptual models that guide planning for marginally successful remedial work to remove the NAPL. Frequently, more time and money is required for remediation than originally predicted, leaving frustrated stakeholders in the wake of the investigation and cleanup efforts.

This article examines some fundamental problems that plague the characterization and cleanup process, and presents some case studies of an improved electrical resistivity imaging (ERI) geophysics approach that yielded innovative views of the subsurface at several difficult sites. Further, these case studies illuminate a relatively new conceptual model for consideration when characterizing and remediating sites.

Specifically, when using ERI geophysics followed by drilling to support the results of the image, NAPL sources in these cases are confirmed to exist as "blobs," not as continuous layers or "plumes" as currently believed by many in the environmental industry. Finding the full extent of NAPL blobs using only conventional drilling techniques is like trying to round up quiet cattle in a dark field, where the end result is that most often some will get away. ERI geophysics can help find the NAPL blobs and often finds the related dissolved-phase impacts, making cleanup strategies more predictable and more reliable.

What's the Problem?

The problem with finding the blobs stems from the fact that real-world sites rarely, if ever, resemble the conceptual model of the idealized site. In the idealized model, NAPL migrates into both the unsaturated and saturated zones as a cohesive mass, ultimately ending up on top of the groundwater table as a layer (Walther et al., 1986). Ultimately, the NAPL begins to dissolve into groundwater and migrate based on groundwater gradient. Simple cartoons that illustrate the idealized conceptual model are generated to indicate how the world works (Schwartz and Zhang, 2003). We call this "the world we would like" conceptual model.

These cartoons are not consistent with the "real world," but unfortunately they are commonly used to form the conceptual model, guiding the decisions that precede the cleanup process. The use of a more sophisticated real world, site-conceptual model has not been practical until recently when ERI geophysics provided a tool that allows one to effectively "see" into the subsurface in a cost-effective and meaningful way.

The real world, site-conceptual model is complex and was previously difficult to impossible to derive. To make matters worse, the NAPL source itself is a cocktail of hundreds of compounds that can vary between refinery locations and season of the year. NAPL can change over time while stored in tanks and will undergo changes once it makes its way into the environment.

The World We Have Model

When NAPL enters the subsurface, it starts migrating in three dimensions as a NAPL source, a dissolved phase in the groundwater, and a vapor in the unsaturated portions of the subsurface. NAPL changes character with time and migrates under various retardation and degradation mechanisms. After some period of time, NAPL sources end up as discrete blobs that are difficult to find using conventional characterization techniques. We call this the "world we have" conceptual model.

The fact that NAPL is observed and migrates as blobs is seen in pore-scale experiments, where NAPL in groundwater disperses as it migrates (Conrad et al., 1992). Similarly on the basin-wide scale, oil fields are not continuous, but occur in distinct patches in a region. This knowledge, plus the data that the new techniques our collective research has developed, is showing us that the world we get is definitely not continuous (Halihan et al., 2005a).

Research and technical practice demonstrates every day that "the world we would like" conceptual model is a failed paradigm and that we collectively need a new "recipe" in the cookbook for environmental cleanups. Abandoning idealized conceptual models and embracing "the world we have" conceptual model makes sense because we get closer to understanding the scope of the true problem, which is the only way an appropriate and cost-effective solution can be developed.

In the idealized "world we would like" paradigm, a project typically starts with drilling and other conventional techniques in the attempt to find and track the NAPL. This site-characterization work is conducted by effectively "drilling blind," and it likely results in undetected NAPL blobs between borings that act as ongoing sources during and after active remediation. In the "world we have" paradigm, the site conceptual model must have field data that locates the blobs, before drilling starts. Therefore, follow-up confirmation drilling is more focused and effective and can provide a predicable and successful exit to a cleanup project.

How About Using Underground "Photography" First?

ERI geophysics is a potentially attractive way to assist in characterizing NAPL-affected sites and is analogous to taking a digital electrical "picture" of the subsurface. Punching holes with direct-push or auger drilling is time consuming and provides a limited one-dimensional sample of the subsurface at a single point in time. Assuming wells are installed, maintained, and monitored properly, the question of what is between adjacent well or boring locations always remains. Most sites that we have examined have wells that are improperly placed, screened in the wrong location, and/or are not in good communication with the groundwater system.

ERI geophysics can provide two- or three-dimensional images (pictures) of the subsurface that provide a more complete understanding of the distribution of NAPL and related contamination. Three-dimensional images can most easily be generated on typical sites by coalescing a set of two-dimensional datasets. The reliability standard to be applied to any geophysical technique, including ERI geophysics, is that the resulting image must be sufficiently accurate so the images have a direct correlation to the subsurface—the images should be "drillable." Without data of this quality, the cost of geophysical techniques does not justify its use in many cases.

ERI geophysics has several attractive qualities for shallow-site investigations (i.e., less than 500 ft). It works in a wide range of natural aquifer materials, is reasonably simple to get accurate measurements, and produces draft images on-site within an hour of completing an ERI geophysical survey. A rapid and accurate result while on-site is very attractive, as investigations can be tailored in real-time.

Proprietary research developed at Oklahoma State University in concert with its commercial partner Aestus Inc., now allows for very accurate pictures of the subsurface that assist in guiding subsequent drilling investigations or remediation. In most cases, high resolution ERI geophysics (commercially available as GeoTrax Survey™ via Aestus Inc.) can be deployed quickly from the surface only, and can provide images at depths within the typical site needs.

The Research Behind the Magic

Much of the initial ERI geophysics research was done through collaborative efforts between Oklahoma State University (OSU), the Oklahoma Corporation Commission, Petroleum Storage Tank Division (PSTD), and Aestus Inc. On one of the PSTD sites, OSU developed a technique to use ERI geophysics in direct-push boreholes so the site could be monitored very accurately over a period of time (Halihan et al., 2005b). The site had relatively simple geology and had not yet been remediated at the start of the project.

The results initially appeared problematic relative to the "world we would like" site-conceptual model that the project team used going into this project. Although the site had a relatively simple geology with clay overlying a sand aquifer, no continuous NAPL plume was apparent in the ERI images.

Instead, separate blobs of NAPLs that correlated with slight variations in the elevation of the clay/sand interface were found. There was no continuous NAPL plume at the groundwater interface, as expected using the "world we would like" conceptual model. After checking the cables, instruments, methodologies, and interpretations, OSU conducted an intensive direct-push coring program to confirm the ERI images. The results of the confirmation-drilling program were completely inconsistent with the conceptual model of a continuous NAPL plume.

The site was sampled using the direct-push methods and some cores indicated high concentrations of NAPL in both the sand and the clay (Figure 1). Other cores indicated high concentrations of NAPL in just the clay, and in other areas, just the sand. In addition, some soil cores were completely clean within a few feet of highly contaminated areas.

In other words, moving the boring location by only a few feet in certain locations would result in data that supported a completely different conceptual model of the site (Figure 1). Therefore, depending on how lucky (or unlucky) the consultant/driller was, the site-conceptual model and hence cleanup strategy would change drastically. In addition, these data clearly did not support the "world we would like" conceptual model with NAPL in a layer on top of the groundwater table.

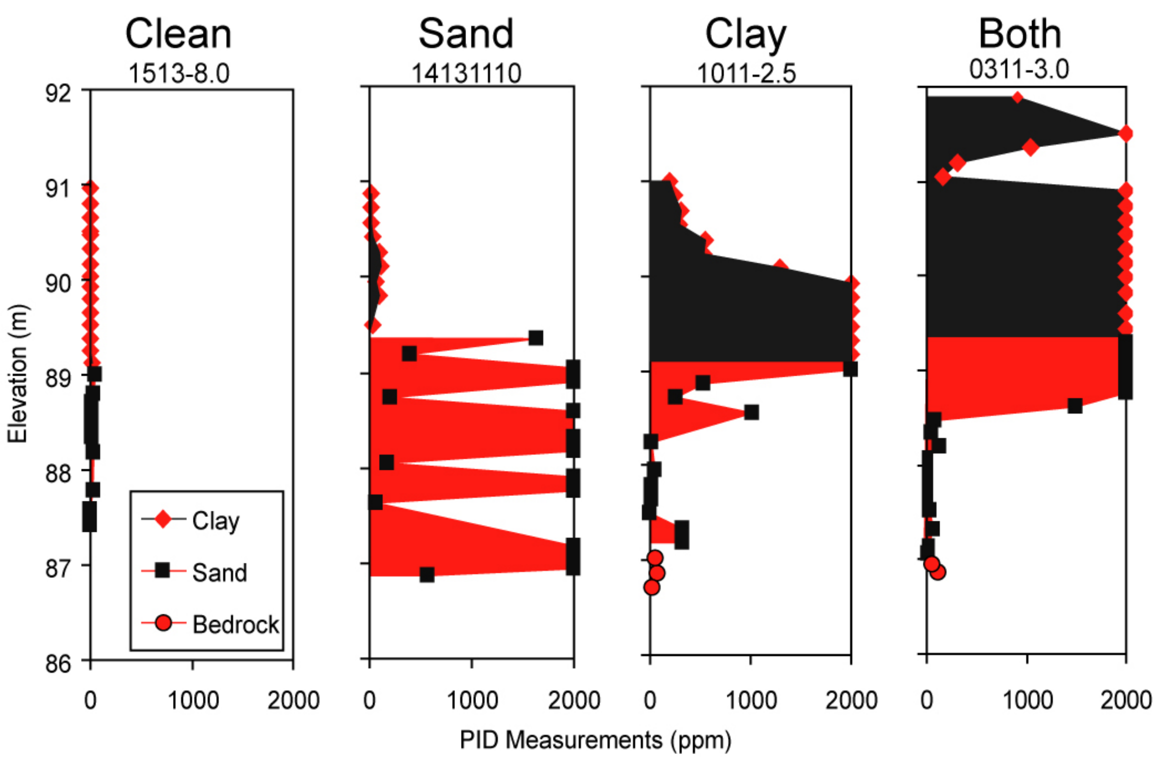

Figure 1. PID readings of NAPL in dual tube direct push cores sampled within 60 feet of each other at a site in Enid, OK. Cores were located using ERI images. Note that each core provides a different conceptual model for the site, but are located close enough to be considered a similar sample location.

When compared, the ERI geophysical image/data matched the drilled core data (Figure 2). It was clear the site-conceptual model needed to change from the “world we would like” to the “world we have” paradigm.

After remediation began at the site, additional ERI geophysical datasets confirmed the blob configuration (Figure 3). The subsequent ERI geophysical data indicated the site was getting dirtier in some areas, not cleaner. The ERI images suggested that previously unmapped hydrocarbons were entering the site from an area that was not originally characterized. The original “world we would like” site-conceptual model of a continuous NAPL plume prevented the original investigators from looking past clean location boundaries, since these edges would have been past the edge of a continuous NAPL plume.

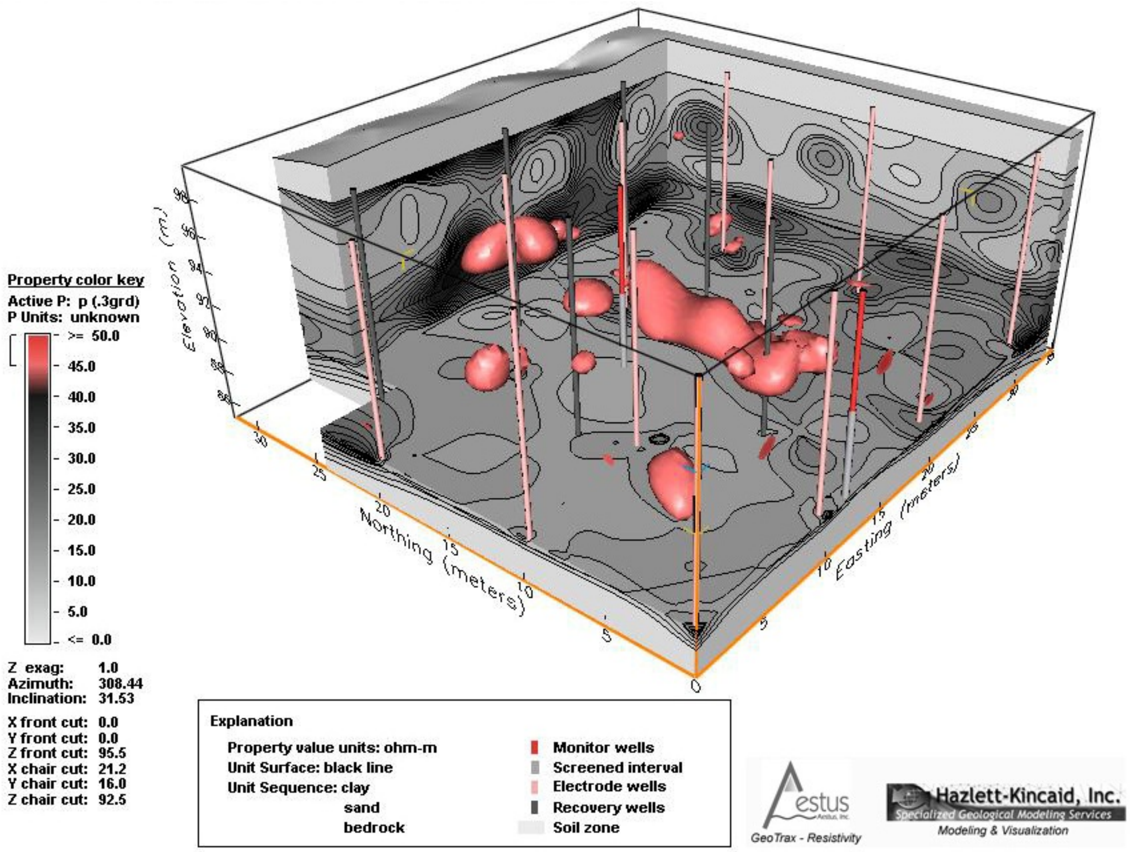

Figure 2. Three-dimensional ERI geophysics of site in Enid, OK prior to site remediation in December 2002. Over 50,000 field data points were collected to generate this image. Image is positioned looking from the southwest towards the northeast. The northwest corner has no data since no cable was located in this position. Fifteen subsurface cables with 27 electrodes each were used to obtain the dataset. The isoshells in red represent the volume of the subsurface that has resistivity above 46 ohm-meters. This is estimated to correspond to the location of free product on the site. The image was produced using data from Oklahoma State University in EarthVision in conjunction with Aestus, Inc. and Hazlett-Kincaid, Inc.

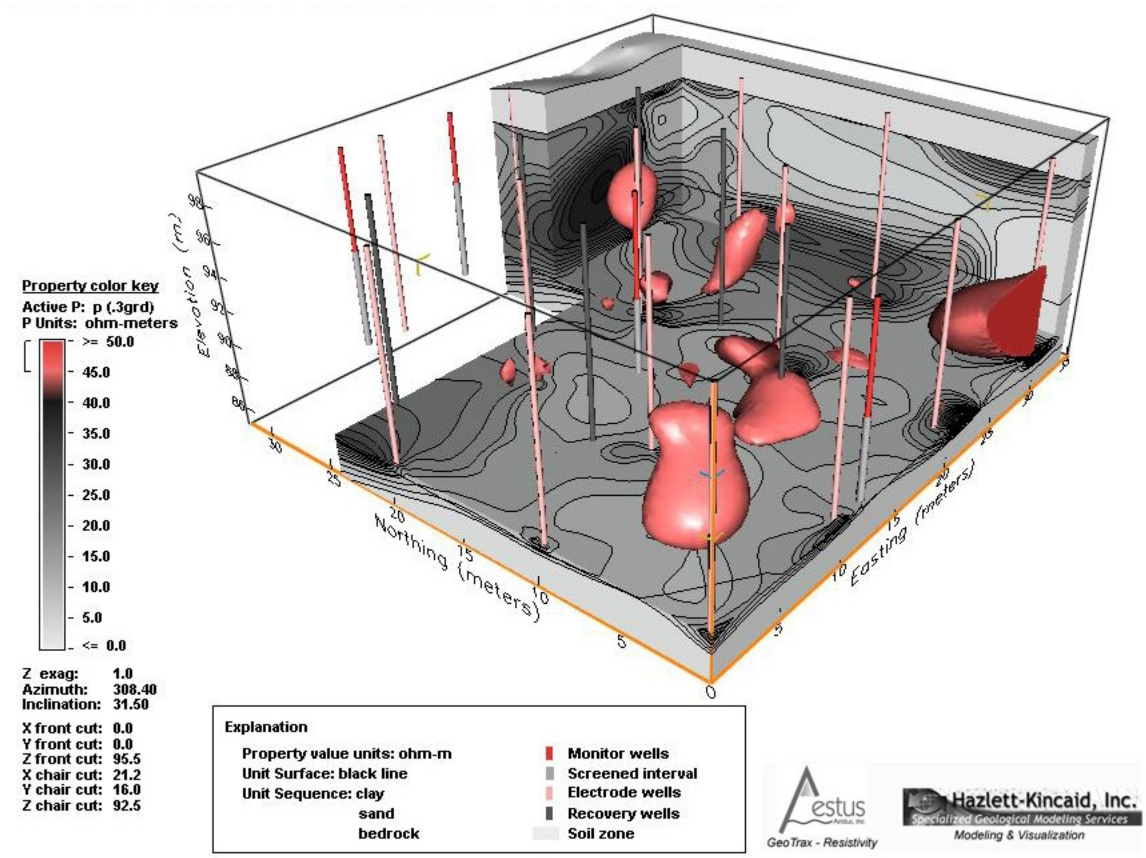

Figure 3. Three dimensional ERI geophysics of site in Enid, OK during site remediation in August 2003. Image is positioned looking from the southwest towards the northeast. The northwest corner has no data since no cables were operational in this position. Thirteen subsurface cables with 27 electrodes each were used to obtain the dataset. The isoshells in red represent the volume of the subsurface that has resistivity above 46 ohm-meters. This is estimated to correspond to the location of free product on the site. Note the new orientation of resistive "blobs" that has occurred since remediation has begun. No significant "blobs" remain within the area enclosed by the remediation wells. The image was produced using data from Oklahoma State University in EarthVision in conjunction with Aestus, Inc. and Hazlett-Kincaid, Inc.

Since the work performed at the Enid, OK site, numerous other sites have been characterized using this improved method for ERI geophysics with similar results. That is, the original site-conceptual model has changed from one that envisioned a continuous NAPL plume, to one with discontinuous NAPL blobs.

Most of the sites characterized by ERI geophysics have been subsequently characterized using drilling techniques. In all cases where confirmation data is available, the ERI images were proven to be correct and the site-conceptual models have improved to include the discontinuous NAPL blob concept.

What You Don't Know Will Hurt You

On many of the sites where improved ERI geophysics has been used and the results confirmed via drilling, NAPL blobs have been discovered in areas thought to be clean or at least devoid of ongoing NAPL sources. The following case studies illustrate why what you don't know will hurt your schedule and your budget, at the very least.

- **Golden, Oklahoma**

  This was a LUST site where characterization was conducted several times via drilling and direct-push (92 monitoring wells were installed in a 5-acre area), and three separate remediation technologies were subsequently deployed. Remediation consisted of standard NAPL removal via pneumatic pumps, soil-vapor extraction, and finally the use of an innovative soil-surfactant flush to achieve predefined cleanup levels. Characterization and remediation was conducted over a 10-year period. About $1.2 million had been expended over this period at this rural site.

  ERI geophysics was deployed at the tail end of this project to evaluate the effectiveness of the cleanup technologies. NAPL blobs were detected outside of the delineated plume at the site (Halihan et al., 2005a). Staff from the U.S. EPA Ground Water and Ecosystems Restoration Research (GWERD) Laboratory in Ada, Oklahoma used the image produced by ERI geophysics and conducted their own drilling program to confirm the ERI image results. EPA advanced seven soil borings within a 50 foot distance along the ERI geophysics survey line in the area of the NAPL blobs (Figure 4). Soil samples were collected about every 6 or 12 inches along the soil core and analyzed for total petroleum hydrocarbon (TPH).

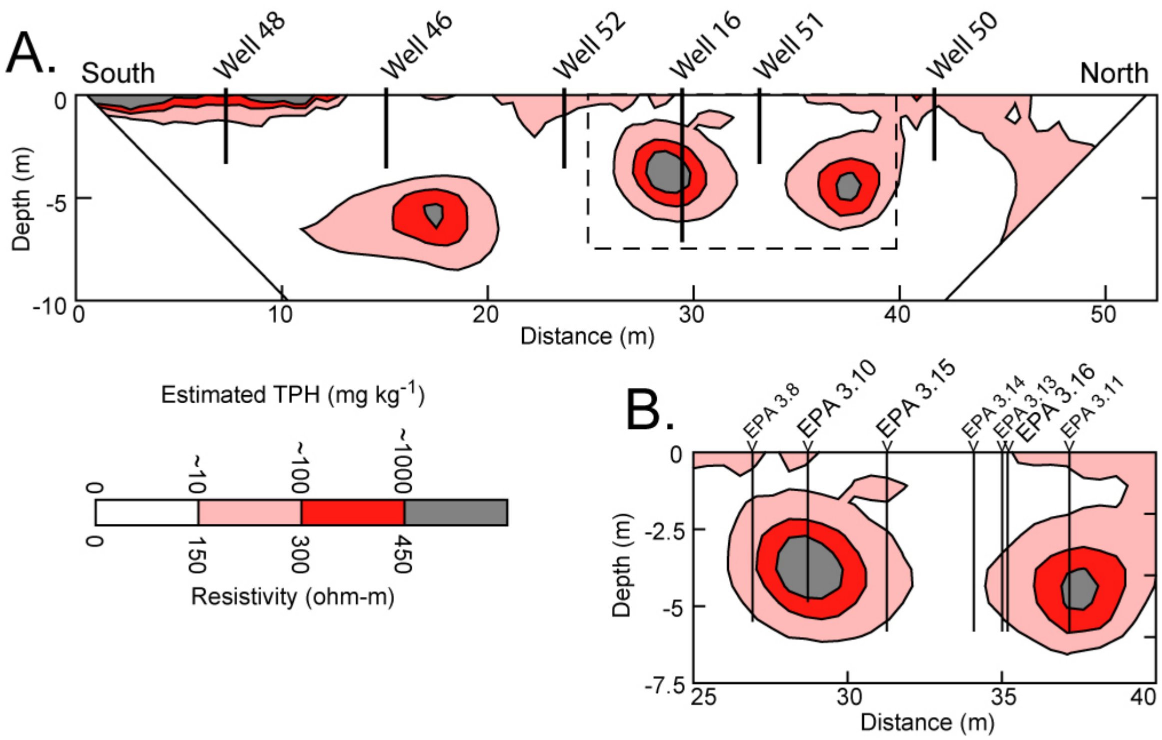

Figure 4. Electrical image EI-2-NS from Golden, OK site (modified from Halihan et al., 2005a). A) Vertical lines in image indicate the location of monitoring and remediation wells. Dotted line indicates area of inset. B) Vertical lines indicate the location of EPA soil borings used to sample high resistivity anomalies. Notes: Estimated TPH values are an approximation, and resistive surface anomalies correspond to soil variability, not hydrocarbon contamination.

EPA's TPH confirmation data indicated a semi-quantitative correlation between TPH concentration and ERI resistivity values. The ERI geophysics data as well as the borings also confirmed that the NAPL blobs existed between the site-remediation wells. Additionally, the highest TPH value ever measured at this site was detected using the ERI geophysics image after all of the characterization and remediation work had already occurred. This ERI geophysics field work was completed in less than one week.

• Hobart, Oklahoma

This site had a significant gasoline vapor intrusion into a nearby State Department of Human Services building, creating health concerns for employees. There were no obvious source sites nearby (e.g., a gas station). A consultant had already characterized the site and had not discovered NAPL sources but did discover high levels of VOCs in the vadose zone. Although a shallow soil vapor-extraction trench was installed next to the building, the vapor intrusion into the building was not fully mitigated.

ERI geophysics was used to survey the area around the building (Figures 5 and 6). The images suggested NAPL sources were slightly deeper than what had previously been the deepest soil boring depth (i.e., greater than 12 feet).

The previous characterization had been conducted using direct-push which encountered refusal from a hard layer at about 12-feet deep. A larger auger-type rig was brought to the site and advanced soil borings to confirm the ERI geophysics image results. In every case where ERI images indicated the likely presence of a NAPL blob, NAPL was discovered in the soil boring. At the conclusion of the ERI geophysics work, a 3-D ERI image was created using a resistivity value roughly equivalent to NAPL locations at this site (Figure 6).

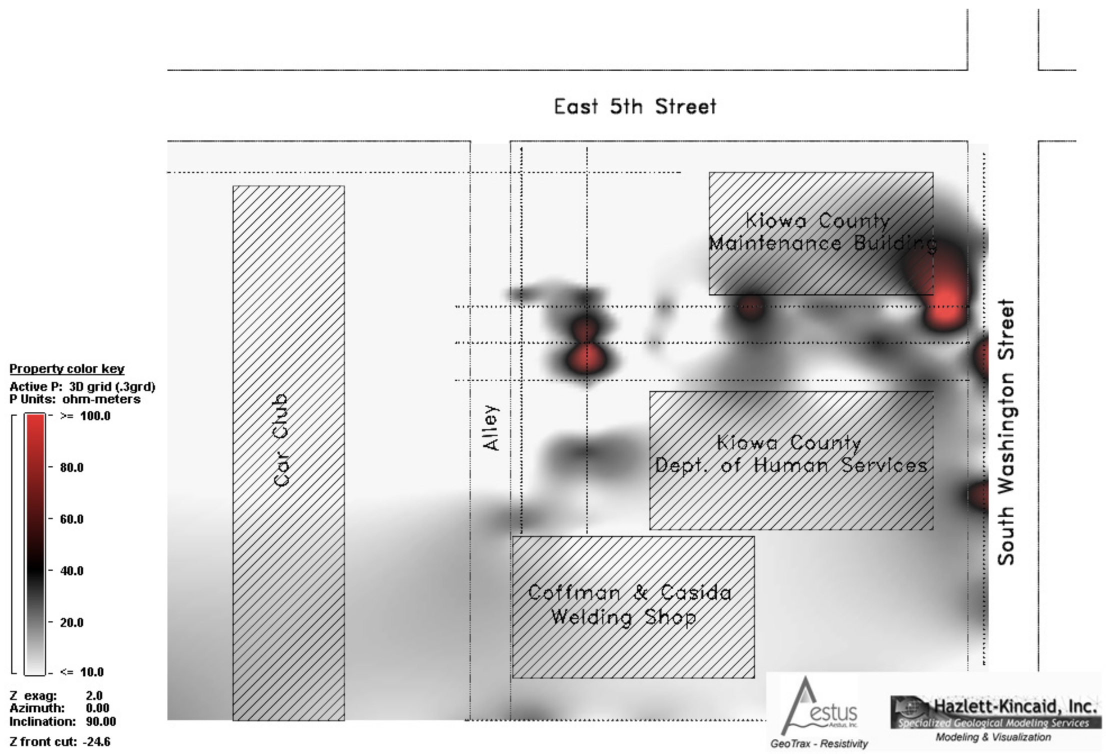

Figure 5. Two-dimensional ERI geophysics of site in Hobart, OK during site characterization. Dotted lines indicate the location of ERI geophysical data lines. Fifty-six electrodes were used to obtain the dataset along each line. The isoshells in red represent the approximate location of free product.

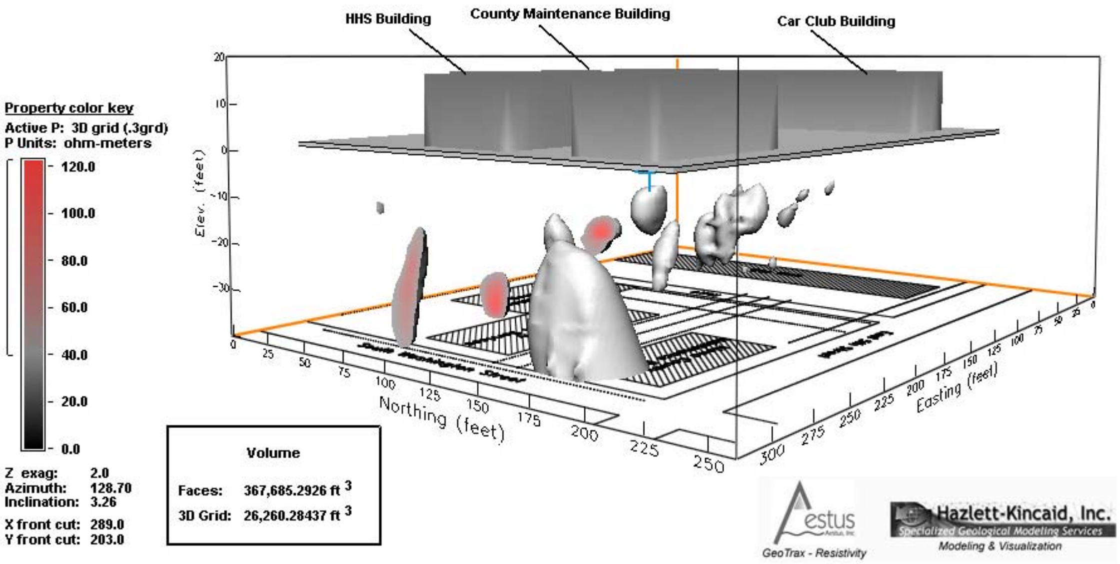

Figure 6. Three dimensional ERI geophysics of site in Hobart, OK during site characterization. Image is positioned looking from the northeast towards the southwest. The isoshells in red represent the approximate volume of the subsurface that has free product on the site. Note the color scale of this figure is slightly different from figure 5 to show detail in each view.

Note, the NAPL blobs were all discovered slightly below the 12-foot depth where the hard layer was encountered by the direct-push rig. Also, some of the NAPL blobs were deeper than the current water table. As a result of this work, the Oklahoma Corporation Commission, PSTD is now considering alternative methods of source removal.

Designing Better Ways to Characterize NAPL Sites

The bottom line is that the LUST cleanup industry needs better tools and a new "recipe" for characterizing NAPL impacted sites. Because drilling alone does not allow NAPL sites to be characterized without significant unknowns, these unknowns often manifest themselves as future liabilities for project stakeholders.

The use of improved characterization techniques/paradigms will lead to more accurate site conceptual models. Such models will ultimately yield more realistic and reliable results during remediation and monitoring phases of these projects. Stakeholders will better understand the extent (or lack of extent) of environmental impacts being addressed and will ultimately become less frustrated. Site remediation will become more predictable, reducing surprises and years of monitoring the unknown.

ERI geophysics has the potential to be integrated throughout various phases of the site cleanup process. As a first step, ERI geophysics can be used to direct the drilling for improved site characterization. During remediation, ERI geophysics can be used to track the progress of remedial efforts. When NAPL removal is believed to be complete, ERI geophysics can be used to confirm that the site is devoid of NAPL blobs. Although this article is focused on NAPL blobs, it should be noted that many case studies exist where ERI geophysics has been successfully used to semi-quantitatively locate and track NAPL-related dissolved-phase contamination in groundwater.

Future Directions

In order to better manage the risks and uncertainties that surround LUST and other environmental site investigations, we believe geophysical techniques will play a significant role. More and more evidence supports the assertion that our current understanding of contaminant behavior in the earth's subsurface is not very good, largely because our view of the world to date has been derived predominately from borings and monitoring wells.

The cost of this poor understanding is far reaching—it costs more money to characterize sites and more time to remediate a site. The impacts may even affect a project stakeholder's company balance sheets via environmental liability reporting. It is critical that we have a good understanding of these sites and a sound site-conceptual model from the outset. We are confident that high-resolution geophysical approaches, tied to confirmation borings, will become the new standard in site characterization, as stakeholders demand more certainty and less risk from their site-remediation investments.

ERI and other techniques will evolve toward full 3-D site characterization methods. The characterization process will require that data are collected and visualized in three dimensions or four dimensions (i.e., 3-D data tracked over time) so stakeholders of all backgrounds can understand the problems and the potential solutions.

Computing and software improvements will drive this process forward, a process that has already occurred in the medical field as CAT-scans, MRIs, and X-Rays have become the first step in that industry's new "recipe" for dealing with "unknown subsurface problems" before operating on a patient.

Historically, the progression of ideas has always evolved from doubt to argument to acceptance and finally to a state of obvious. What is originally controversial becomes obvious and other ways of approaching environmental problems become quaint or "old-school." We should always remember that young technologies need to be introduced to the world with a little care, and that those that become proven will help us foster the health of the environment.

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